Towards an understanding of heavy baryon spectroscopy

A. Valcarce,[1] H. Garcilazo,[2] and J. Vijande[3]

[1]*Departamento de Física Fundamental, Universidad de Salamanca, E-37008 Salamanca, Spain*

[2]*Escuela Superior de Física y Matemáticas, Instituto Politécnico Nacional, Edificio 9, 07738 México D.F., Mexico*

[3]*Departamento de Física Teórica e IFIC, Universidad de Valencia - CSIC, E-46100 Burjassot, Valencia, Spain*

(Dated: July 18, 2008)

Abstract

The recent observation at CDF and D0 of Σ_b, Σ_b^* and Ξ_b baryons opens the door to the advent of new states in the bottom baryon sector. The states measured provide sufficient constraints to fix the parameters of phenomenological models. One may therefore consistently predict the full bottom baryon spectra. For this purpose we have solved exactly the three-quark problem by means of the Faddeev method in momentum space. We consider our guidance may help experimentalists in the search for new bottom baryons and their findings will help in constraining further the phenomenological models. We identify particular states whose masses may allow to discriminate between the dynamics for the light-quark pairs predicted by different phenomenological models. Within the same framework we also present results for charmed, doubly charmed, and doubly bottom baryons. Our results provide a restricted possible assignment of quantum numbers to recently reported charmed baryon states. Some of them are perfectly described by $D-$wave excitations with $J^P = 5/2^+$, as the $\Lambda_c(2880)$, $\Xi_c(3055)$, and $\Xi_c(3123)$.

PACS numbers: 12.39.Jh, 12.39.Pn, 14.20.-c

I. INTRODUCTION

The last year has witnessed an amazing experimental progress in the identification of new bottom baryon states. Last June CDF [1] reported the first observation of the $\Sigma_b^{\pm}$, uub and ddb states with $J^P = 1/2^+$, and $\Sigma_b^{\star\pm}$, uub and ddb states with $J^P = 3/2^+$. The observed values were

$$\begin{aligned} M(\Sigma_b^-) &= 5815.2 \pm 1.0(\mathrm{stat}) \pm 1.7(\mathrm{syst})\,\mathrm{MeV/c^2}\,, \\ M(\Sigma_b^+) &= 5807.8^{+2.0}_{-2.2}(\mathrm{stat}) \pm 1.7(\mathrm{syst})\,\mathrm{MeV/c^2}\,; \end{aligned} \tag{1}$$

and

$$\begin{aligned} M(\Sigma_b^{\star -}) &= 5836.4^{+2.0}_{-1.8}(\mathrm{stat})\ {}^{+1.8}_{-1.7}(\mathrm{syst})\,\mathrm{MeV/c^2}\,, \\ M(\Sigma_b^{\star +}) &= 5829.0^{+1.6}_{-1.8}(\mathrm{stat})\ {}^{+1.7}_{-1.8}(\mathrm{syst})\,\mathrm{MeV/c^2}\,. \end{aligned} \tag{2}$$

During June and July CDF [2] and D0 [3] reported the observation of the baryon Ξ_b^-, dsb state with $J^P = 1/2^+$,

$$\begin{aligned} M(\Xi_b^-) &= 5792.9 \pm 2.5(\mathrm{stat})\ \pm 1.7(\mathrm{syst})\,\mathrm{MeV/c^2}\ (\mathrm{CDF})\,, \\ M(\Xi_b^-) &= 5774 \pm 11(\mathrm{stat})\ \pm 15(\mathrm{syst})\,\mathrm{MeV/c^2}\ (\mathrm{D0})\,. \end{aligned} \tag{3}$$

The number of known bottom baryons increased from one to four over a few months, determining for the first time the hyperfine splitting in the bottom sector.

Heavy hadrons containing a single heavy quark are particularly interesting. The light degrees of freedom (quarks and gluons) circle around the nearly static heavy quark. Such a system behaves as the QCD analogue of the familiar hydrogen bounded by the electromagnetic interaction. When the heavy quark mass $m_Q \to \infty$, the angular momentum of the light degrees of freedom is a good quantum number. Thus, heavy quark baryons belong to either SU(3) antisymmetric $\bar{\mathbf{3}}_{\mathbf{F}}$ or symmetric $\mathbf{6}_{\mathbf{F}}$ representations. The spin of the light diquark is 0 for $\bar{\mathbf{3}}_{\mathbf{F}}$, while it is 1 for $\mathbf{6}_{\mathbf{F}}$. Thus, the spin of the ground state baryons is 1/2 for $\bar{\mathbf{3}}_{\mathbf{F}}$, representing the Λ_b and Ξ_b baryons, while it can be both 1/2 or 3/2 for $\mathbf{6}_{\mathbf{F}}$, allocating Σ_b, Σ_b^*, Ξ_b', Ξ_b^*, Ω_b and Ω_b^*, where the star indicates spin 3/2 states. Therefore heavy hadrons form doublets. For example, Σ_b and Σ_b^* will be degenerate in the heavy quark limit. Their mass splitting is caused by the chromomagnetic interaction at the order $1/m_Q$. These effects can be, for example, taken into account systematically in the framework of heavy quark effective field theory (HQET). The mass difference between states belonging to the $\bar{\mathbf{3}}_{\mathbf{F}}$ and $\mathbf{6}_{\mathbf{F}}$ representations do also contain the dynamics of the light diquark subsystem, hard to accommodate in any heavy quark mass expansion. Therefore, exact solutions of the three-body problem for heavy hadrons are theoretically desirable because they will serve to test the reliability of approximate techniques, that would only be exact in the infinite heavy-quark mass limit, as could be heavy quark mass expansions, variational calculations, or quark-diquark approximations.

Heavy baryons, charmed and/or bottom, have been the matter of study during the last two decades [4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19]. After the discovery of the first charmed baryons, several theoretical works [4, 5, 6] based on potential models developed for the light baryon or meson spectra started analyzing properties of the observed and expected states. Later on, Capstick and Isgur [7] studied heavy baryon systems in a relativized quark potential model applying a variational approach to obtain the mass eigenvalues and bound state wave functions by using a harmonic oscillator basis. Roncaglia

et al. [8] predicted the masses of baryons containing one or two heavy quarks using the Feynman-Hellmann theorem and semiempirical mass formulas. Silvestre-Brac [9] studied ground state charmed and bottom baryons using Faddeev equations in configuration space. Excited states were studied by diagonalization in a harmonic oscillator basis up to eight quanta. Jenkins [10] studied heavy baryon masses in a combined expansion in $1/m_Q$, $1/N_c$, and SU(3) flavor symmetry breaking. Bowler *et al.* [11] made an exploratory study using lattice techniques to predict charmed and bottom baryons. Mathur *et al.* [12] gave a more precise prediction of the masses of charmed and bottom baryons from quenched lattice QCD. Ebert *et al.* [13] calculated the masses of ground state heavy baryons with the relativistic quark-diquark approximation. QCD sum rule has been also applied to study heavy baryon masses [14, 15]. Stimulated by the recent experimental progress, there have been several theoretical papers on the masses of Σ_b, Σ_b^* and Ξ_b or the full bottom baryon spectra using a perturbative treatment of the hyperfine interaction in the quark model [16], heavy quark effective field theory [17], a variational calculation in a harmonic oscillator expansion [18], and a relativistic quark-diquark approximation [19].

While the mass of heavy baryons is measured as part of the discovery process, no spin or parity quantum numbers of a given state have been measured experimentally, but they are assigned based on quark model expectations. Such properties can only be extracted by studying angular distributions of the particle decays, that are available only for the lightest and most abundant species. For excited heavy baryons the data set are typically one order of magnitude smaller than for heavy mesons and therefore the knowledge of radially and orbitally excited states is very much limited. Unlike the heavy mesons there are no resonant production mechanisms and thus heavy baryons can only be obtained by continuum production, where cross sections are small. As a consequence the B factories have been the main source of these baryons. Therefore, a powerful guideline for assigning quantum numbers to new states or to indicate new states to look for is required by experiment. We do understand ground state heavy quark baryons, both in the quark model and in the lattice QCD. The main issue is therefore to determine quantum numbers of excited states. Here, a coherent theoretical and experimental effort is required.

Apart from CDF and D0 data, putting into operation the Large Hadron Collider (LHC) will provide us with data on masses of excited bottom baryons. Therefore the calculation of the mass spectra of excited heavy baryons turns out to be a really actual problem. Here we consider the exact calculation of ground states, spin, radial and orbital excitations of bottom baryons in a model constrained to reproduce the new recent experimental data. These new experimental data give rise to a spin splitting of the order of 25 MeV, much smaller that previous experimental expectations, of the order of 50 MeV [11, 20]. Using the same phenomenological model we also calculate the charmed baryon spectra showing the nice agreement of our predictions with recently measured states, what will allow to assign their spin and parity quantum numbers. We will finally consistently present our predictions for doubly bottom and charmed baryons.

II. FORMALISM AND RESULTS

Nowadays, we have to our disposal *realistic* quark models accounting for most part of the one- and two-body low-energy hadron phenomenology. The ambitious project of a simultaneous description of the baryon-baryon interaction and the baryon (and meson) spectra has been undertaken by the constituent quark model of Ref. [21]. The success in describing the

properties of the strange and non-strange one and two-hadron systems encouraged its use as a guideline in order to assign parity and spin quantum numbers to already determined heavy baryon states as well as to predict still non-observed resonances [22]. The constituent quark model used considers perturbative (one-gluon exchange) and nonperturbative (confinement and chiral symmetry breaking) aspects of QCD, ending up with a quark-quark interaction of the form

$$V_{q_iq_j} = \begin{cases} q_iq_j = nn/sn \Rightarrow V_{CON} + V_{OGE} + V_\chi \\ q_iq_j = cn/cs/bn/bs/cc/bb \Rightarrow V_{CON} + V_{OGE} \end{cases} , \quad (4)$$

where V_{CON} stands for a confining interaction, V_{OGE} for a one-gluon exchange potential, and V_χ for scalar and pseudoscalar boson exchanges. For heavy quarks (c or b) chiral symmetry is explicitly broken and boson exchanges do not contribute. For the explicit expressions of the interacting potential and a more detailed discussion of the model we refer the reader to Refs. [23, 24]. For the sake of completeness we resume the parameters of the model in Table I. The results have been obtained by solving exactly the Schrödinger equation by the Faddeev method in momentum space [21].

The recent observation of ground state Σ_b and Σ_b^* baryons provides with all necessary ingredients to fix the model parameters and therefore make univocal predictions for all remaining bottom baryon states: spin, radial and orbital excitations. Once the model is fixed we can also derive the spectra for doubly charmed and doubly bottom baryons. Besides we can revisit the charmed baryon sector, centering our attention in some states recently reported in an attempt to help in the assignment of spin and parity quantum numbers. Finally, our results will allow us to check equal spacing rules derived from heavy quark symmetry and chiral symmetry.

Our results for bottom baryons are shown in Table II compared to experiment and other theoretical approaches. We present our predictions for spin, radial and orbital excitations. All known experimental data are nicely described. Such a remarkable agreement and the exact method used to solve the three-body problem make our predictions highly valuable as a guideline to experimentalists. They should also serve to guide theoretical calculations using approximate methods.

As compared to other results in the literature we see an overall agreement for the low-lying states both with the quark-diquark approximation of Ref. [19] and the variational calculation in a harmonic oscillator basis of Ref. [18]. Some differences appear for the excited states that we will analyze in the following and that could be either due to the interacting potential or to the method used to solve the three-body problem. The relativistic quark-diquark approximation of Ref. [19] predicts a larger radial excitation for negative parity states (except for the Ξ_b baryon) as compared to any other result in the literature. We do not see any explanation for this result. The relativistic quark-diquark approximation and the harmonic oscillator variational method predict a lower $3/2^+$ excited state for the Λ_b baryon. Such result can be easily understood by looking at Table III, where it is made manifest the influence of the pseudoscalar interaction between the light quarks on the $\Lambda_b(1/2^+)$ ground state, diminishing its mass by 200 MeV. If this attraction would not be present for the $\Lambda_b(1/2^+)$, the $\Lambda_b(3/2^+)$ would be lower in mass as reported in Refs. [18, 19] (a similar effect will be observed in the charmed baryon spectra). Thus, the measurement and identification of the $\Lambda_b(3/2^+)$ is a relevant feature that will help to clarify the nature of the interaction between the light quarks in heavy baryon spectroscopy, determining the need of pseudoscalar forces consequence of the spontaneous chiral symmetry breaking in the light flavor sector.

Let us revise our results in connection with the interacting potential used. The first

ingredient of any quark potential model is confinement. Confinement is supposed to be flavor independent and therefore it should be fixed in one flavor sector once for all. As mentioned above, knowledge of orbital and radial excited states is very much limited for heavy baryons. Thus, guidance for the confinement strength should be taken from the light baryon sector. The non-strange baryon sector is the best known one from the spectroscopic point of view. However it is delicate to fix the confinement strength due to the particular nature of the radial excitation, the Roper resonance. In Refs. [25] it has been shown the sensitivity of the Roper resonance to relativistic kinematics, justifying the use of negative parity states to fix the confinement strength when working in a non-relativistic framework. The strength of confinement quoted in Table I gives a good overall agreement with the N and Δ spectra.

Once the confinement strength has been fixed in the light flavor sector, we note that the radial excitation of $1/2^+$ bottom baryons is predicted around 450 MeV above the ground state. The only exception is the $\Xi_b(1/2^+)$ with an excitation energy, $1/2^+ - 1/2'^+$, around 140 MeV. This resonance is not indeed a radial excitation. The ground state corresponds to a us pair in a dominant singlet spin state while the excited state corresponds to the same pair in a dominant triplet spin state. These two levels are often denoted in the literature as $\Xi_b(1/2^+)$ and $\Xi'_b(1/2^+)$, the same notation we will use in this work. As can be seen in Table II their radial excitations also appear 450 MeV above the corresponding ground state. At difference of other calculations in the literature where the Ξ_b and Ξ'_b baryons are pure scalar or vector light diquark states [18, 19] (mixed is some cases perturbatively), our calculation includes all possible channels contributing to each state. The similar results obtained indicate a small admixture of scalar and vector diquarks in nature. We consider very important that the analysis of the different flavor sectors is done in terms of the same flavor-independent forces to obtain conclusions about the rest of the dynamical model. This is not often mentioned in the literature.

Our screened confining potential would give rise at short range to a linear potential with a strength of about 600 MeV fm^{-1}. This value is very close to the string tension obtained in Ref. [26] from the bottomonium spectrum, $\sqrt{\kappa} = 440-480$ MeV, that would translate into a linear confinement strength of the same order, around $500-600$ MeV fm^{-1}. In contrast, for example, Ref. [18] uses a smaller confining strength of the order of 400 MeV fm^{-1}. Maybe this is one of the reasons why they use a negligible coulomb strength.

Being the confinement strength determined in the light baryon sector, heavy baryons are ideal systems to study the flavor dependence of the spin splitting, mass difference between $\Sigma_b(3/2^+) \equiv \Sigma_b^*$ and $\Sigma_b(1/2^+) \equiv \Sigma_b$. Such systems present, on one hand, the dynamics of the two-light quarks involving potentials coming from the chiral part of the interaction and, on the other hand, the dynamics of heavy-light subsystems. The dynamics of the light diquark subsystem is fully determined in studying the light-baryon spectra, and therefore its contribution to the spin splitting. Thus, the remaining spin splitting must be due to the interaction between the heavy and the light quarks. The recent measurement of Σ_b and Σ_b^* states determines in a unique way the color-magnetic interaction between the light and the b quark, allowing a parameter free prediction of all other states of the bottom spectra. A relevant conclusion of the study of the spin splitting for bottom baryons is that while for similar mass quark pairs one can use for the regularization parameter of the color-magnetic one-gluon exchange interaction, r_0, a formula depending on the reduced mass of the system (this has been proved in the past [9, 24]), however, when the masses of the interacting quarks are quite different (the case of heavy baryons), a reduced mass based formula is not adequate.

Such a formula will give the same result, for example, for a light-charm than for a light-bottom pair. As the color-magnetic term of the one-gluon exchange interaction depends on the inverse of the product of the masses of the interacting quarks, such a potential will be strongly reduced for the heavier pair producing a too small spin-splitting.

We are thus led to the interplay between the pseudoscalar and the one-gluon exchange interactions, a key problem for both the baryon spectra and the two-nucleon system [27]. This can be illustrated noting that while the $\Sigma_i(3/2^+) - \Lambda_i(1/2^+)$ mass difference varies slowly from the strange to the bottom sector, the $\Sigma_i(3/2^+) - \Sigma_i(1/2^+)$ mass difference varies very fast (see Table IV). As discussed in the introduction, the former is a mass difference between members of the $\mathbf{\bar{3}_F}$ and $\mathbf{6_F}$ SU(3) representations and therefore it presents contributions from the pseudoscalar and one-gluon exchange forces (see columns V_1 and V_3 of Table III in Ref. [24]). However, the latter is a mass difference between members of the same representation, $\mathbf{6_F}$, and it is therefore uniquely due to the one-gluon exchange interaction between the light diquark and the heavy quark. This can be easily understood by explicit construction of the spin-flavor wave-function. In the case of Λ baryons the two light quarks are in a flavor antisymmetric spin 0 state, the pseudoscalar and the one-gluon exchange forces being both attractive. For Σ baryons they are in a flavor symmetric spin 1 state. The pseudoscalar force, being still attractive, is suppressed by one order of magnitude due to the expectation value of the $(\vec{\sigma}_i \cdot \vec{\sigma}_j)(\vec{\lambda}_i \cdot \vec{\lambda}_j)$ operator [24] and the one-gluon exchange between the two light quarks becomes repulsive. Therefore, the attraction is provided by the interaction between the light diquark and the heavy quark, which for heavy quarks c or b is given only by the one-gluon exchange potential.

The above discussion is explicitly illustrated in Table III, where we have calculated the mass of Σ_i and Λ_i ($i = s$ or b) baryons with and without the pseudoscalar exchange contribution. As can be seen the effect of the pseudoscalar interaction between the two-light quarks is approximately the same independently of the third quark. As the mass difference between the $\Sigma_i(3/2^+)$ and $\Sigma_i(1/2^+)$ states decreases when increasing the mass of the baryon, being almost constant the effect of the one pion-exchange, the remaining mass difference has to be accounted for by the one-gluon exchange (mass difference between states belonging to the $\mathbf{6_F}$ representation). This rules out any ad hoc recipe for the relative strength of both potentials, what would be in any manner consistent with experiment, and it also reinforces the importance of constraining models for the baryon spectra in the widest possible set of experimental data. Thus, Table III shows how for heavy quark baryons the dynamics of any two-particle subsystem is not affected by the nature of the third particle. As a consequence, the regularization parameter of the one-gluon exchange potential should depend on the interacting pair, independently of the baryon the pair belongs to. The values of r_0 reproducing the experimental data are quoted in Table V. They obey a formula depending on the product of the masses of the interacting quarks that can be represented by $r_0^{q_i q_j} = A\mu \left(m_{q_i} m_{q_j}\right)^{-3/2}$, where A is a constant and μ the reduced mass of the interacting quarks. While working with almost equal or not much different masses this law can be easily replaced by a formula depending on some inverse power of the mass (or reduced mass) of the pair as obtained in Ref. [23], but this is not any more the case for quarks with very different masses, like those present in heavy baryons. This is one of the reasons why these systems constitute an excellent laboratory for testing low-energy QCD realizations.

Based on our exact method for the solution of the three-body problem, let us analyze the predictions derived from heavy-quark symmetry (HQS) and chiral symmetry combined together in order to describe the soft hadronic interactions of hadrons containing a heavy

quark [28]. In the limit of the heavy quark mass $m_Q \to \infty$, HQS predicts that all states in the $\mathbf{6_F}$ SU(3) representation (those where the light degrees of freedom are in a spin 1 state) would be degenerate. If one considers HQS and lowest order SU(3) breaking [29] the masses of heavy baryons obey an equal spacing rule, similar to the one that arises in the decuplet of light $J^P = 3/2^+$ baryons, it reads

$$\begin{aligned} J = 1/2 \ : \ M_{\Sigma_b} + M_{\Omega_b} &= 2\,M_{\Xi'_b} \\ J = 3/2 \ : \ M_{\Sigma^*_b} + M_{\Omega^*_b} &= 2\,M_{\Xi^*_b}\,. \end{aligned} \tag{5}$$

This equal spacing rule also holds for the hyperfine splittings

$$\delta_{\Sigma_b} + \delta_{\Omega_b} = 2\,\delta_{\Xi_b}\,, \tag{6}$$

where $\delta_{\Sigma_b} = M_{\Sigma^*_b} - M_{\Sigma_b}$, $\delta_{\Xi_b} = M_{\Xi^*_b} - M_{\Xi'_b}$, and $\delta_{\Omega_b} = M_{\Omega^*_b} - M_{\Omega_b}$. The latter relation is expected to be more accurate than Eq. (5) [10] and it is exactly fulfilled by our results as it is shown in Table VI. Combining Eqs. (5) and (6), one arrives to the approximate relations,

$$\begin{aligned} \Xi'_b(1/2^+) - \Sigma_b(1/2^+) &= \Omega_b(1/2^+) - \Xi'_b(1/2^+) = \\ = \Xi_b(3/2^+) - \Sigma_b(3/2^+) &= \Omega_b(3/2^+) - \Xi_b(3/2^+)\,. \end{aligned} \tag{7}$$

These relations are satisfied by experimental data in the case of charmed baryons with differences of the order of 10 MeV, what gives an idea of the breaking of the SU(3) flavor symmetry. These predictions are clearly sustained by our model to the same precision as can be checked in Table VII. Therefore our dynamical model incorporates the features of broken SU(3) flavor symmetry and heavy-quark expansion of QCD in a reasonable way. Let us note that one-gluon exchange based models do almost satisfy exactly Eq. (7) (results of Refs. [9] and [18] in Table VII) probably due to the absence of SU(3) flavor symmetry breaking interactions. It is also interesting to note that lattice calculations based on HQS fulfill exactly Eq. (7) for charmed baryons [11] while the disagreement is very large for bottom baryons (results of Ref. [11] in Table VII).

To have the widest set of predictions within the same model we have calculated the charmed baryon spectra. The results are shown in Table VIII. In this case the masses of several ground and excited states are known. They fit nicely within our results based on the quantum numbers assigned by the PDG using quark model arguments. There are some excited charmed baryons that it is not even known if they are excitations of the Λ_c or Σ_c. The first one is a resonance at 2765 MeV reported by CLEO in Ref. [30], that could be either a Λ_c or a Σ_c baryon. The original reference suggested the possibility of a Σ_c state with $J^P = 1/2^-$. For this state our calculation shows a perfect agreement with the suggested nature and quantum numbers, although one could not discard this state being the first radial excitation $2S$ of the Λ_c with $J^P = 1/2^+$, as has been suggested in Refs. [13, 18]. The $\Lambda_c(2880)$ is perfectly described by the two possibilities suggested by experiment: either an orbital excitation $2P$ of the Λ_c with $J^P = 1/2^-$, as conjectured by CLEO in Ref. [30] due to the observation of decay via $\Sigma_c\pi$ but not via $\Sigma^*_c\pi$, or an orbital excitation $1D$ of the Λ_c with $J^P = 5/2^+$, in agreement with the recent spin assignment by Belle based on the analysis of angular distributions in the decays $\Lambda_c(2880)^+ \to \Sigma_c(2455)^{0,++}\pi^{+,-}$ [31]. Our model also predicts the resonance at 2940 MeV recently reported by BaBar in Ref. [32] being the first radial excitation $2S$ of the Σ_c with $J^P = 3/2^+$. Finally, the $\Sigma_c(2800)$ may correspond to the second state of the lowest P wave multiplet with $J^P = 3/2^-$, very close to its $1/2^-$ partner

at 2765 MeV. A number of new Ξ_c and Ξ_c' states have been also discovered recently. Two resonances at 3055 and 3123 MeV have been reported by BaBar in Ref. [33]. They fit into the doublet of orbital excited states $2D$ with $J^P = 5/2^+$, the first one with the light diquark in a spin 0 state, Ξ_c, and the second in a spin 1 state, Ξ_c'. For the second resonance one cannot discard the first radial excitation $2S$ of the Ξ_c (light diquark in a spin 0 state) with $J^P = 1/2^+$ as suggested in Ref. [18]. Belle, in Ref. [34], has reported two resonances at 2980 and 3076, while the first one may correspond to the first radial excitation $2P$ of the Ξ_c with $J^P = 1/2^-$, the second clearly corresponds to the first radial excitation $2S$ of the Ξ_c with $J^P = 3/2^+$. As can be seen all known experimental states fit nicely into the description of our model not leaving too many possibilities open for the assigned quantum numbers as we have resumed in Table IX.

Finally, we can easily extend our predictions to doubly bottom and charmed baryons. A few years ago the SELEX Collaboration [35] reported the discovery of a baryon with a mass of 3519 GeV that they concluded could be a doubly charmed Ξ_{cc} state. The attempts to confirm such discovery by BaBar [36], Belle [37], and FOCUS [38] Collaborations have failed. Potential models based on chromomagnetic interactions predict for this state larger masses [18]. In our case we can make parameter free predictions for ground states as well as for spin, orbital and radial excitations. The ground state is found to be at 3579 MeV, far below the result of Ref. [18] and in perfect agreement with lattice nonrelativistic QCD [12], but still a little bit higher than the non-confirmed SELEX result. It is therefore a challenge for experimentalists to confirm or to find the ground state of doubly charmed and bottom baryons.

The combined study of Qqq and QQq systems, where Q stands for a heavy c or b quark and q for a light u, d, or s quark, will also provide some hints to learn about the basic dynamics governing the interaction between light quarks. The interaction between pairs of quarks containing a heavy quark Q is driven by the perturbative one-gluon exchange. This has been demonstrated by quenched and unquenched lattice QCD calculations [26]. The important issue of the simultaneous study of these two types of heavy baryons, is the presence in one of them of a pair of light quarks. As explained above, for the Qqq system the mass difference between members of the $\mathbf{6_F}$ SU(3) representation comes determined only by the perturbative one-gluon exchange, whether between members of the $\mathbf{6_F}$ and $\mathbf{\bar{3}_F}$ representations it presents contributions from the one-gluon exchange and also possible pseudoscalar exchanges. If the latter mass difference would be attributed only to the one-gluon exchange (this would be the case of models based only on the perturbative one-gluon exchange), it will be strengthened as compared to models considering pseudoscalar potentials at the level of quarks, where a weaker one-gluon exchange will play the role. When moving to the QQq systems only one-gluon exchange interactions between the quarks will survive, with the strength determined in the Qqq sector, where we have experimental data. This will give rise to larger masses for the ground states, due to the more attractive one-gluon exchange potential in the Qqq sector, what requires larger constituent quark masses to reproduce the experimental data. This could be the reason for the larger masses of ground state doubly heavy baryons obtained with gluon-based interacting potentials [7, 18].

Therefore, among the baryons with two heavy quarks the first question to be settled is where do exactly these states lie. In case such low masses as those reported by SELEX were confirmed theorists will have a challenge to accommodate this state into the nice description of charmed and bottom baryons. Their exact mass may help in discriminating between the dynamics of the light degrees of freedom of the different models. In any case, the excited

spectra of doubly charmed and bottom baryons do not depend much on the mass of the heavy quarks, and therefore the predicted excited spectra should serve as a guideline for potential future experiments looking for such states. Our results for the ground and excited spectra are resumed in Tables X and XI compared to those of Refs. [8, 9, 12, 18]. As can be seen the radial excitations of Ref. [18] are lower than in our model, due to the small confining strength used. We also note some unexpected results in Ref. [18] as the reverse of the hierarchy in the spin splitting between Ξ_{bb} and Ω_{bb} compared to Ξ_{cc} and Ω_{cc}, what could be a misprint in this reference.

III. SUMMARY

We have used a constituent quark model incorporating the basic properties of QCD to study the bottom baryon spectra. Consistency with the light baryon spectra and the new experimental data reported by CDF allow to fix all model parameters. The model takes into account the most important QCD nonperturbative effects: chiral symmetry breaking and confinement as dictated by unquenched lattice QCD. It also considers QCD perturbative effects trough a flavor dependent one-gluon exchange potential. We make a parameter free prediction of the spin, orbital and radial excitations. We have predicted the spectra of doubly bottom and charmed baryons. We have also revisited the charmed baryon spectra finding a nice agreement with the recently reported data what allowed to make a restricted assignment of their spin and parity quantum numbers.

Our results have been obtained by solving exactly the three-body problem by means of the Faddeev method in momentum space. In spite of the huge computer time needed to obtain the set of results presented in this work, such effort should be highly valuable both from the theoretical and experimental points of view. Theoretically, it should be a powerful tool for testing different approximate methods to solve the three-body problem in the large mass limit for one or two of the components. Experimentally, the remarkable agreement with known experimental data make our predictions highly valuable as a guideline to experimentalists.

The flavor independence of the confining potential has been used to describe all flavor sectors. We have identified particular states of single heavy baryons whose masses will be clearly different depending on the particular dynamics governing the interaction between the two light quarks. The measurement and identification of the $\Lambda_i(3/2^+)$ ($i = c$ or b) will provide enough information to distinguish between the two alternatives for the light quark dynamics: only gluon exchanges or gluon supplemented by pseudoscalar forces. In our description we notice a key interplay between pseudoscalar and one-gluon exchange forces, already observed for the light baryons, that may constitute a basic ingredient for the description of heavy baryons. The final spectra results from a subtle but physically meaningful balance between different spin-dependent forces. The baryon spectra make manifest the presence of two different sources of spin-dependent forces that can be very well mimic by the operatorial dependence generated by the pseudoscalar and one-gluon exchange potentials.

Heavy baryons constitute an extremely interesting problem joining the dynamics of light-light and heavy-light subsystems in an amazing manner. While the mass difference between members of the same SU(3) configuration, either $\mathbf{\bar{3}_F}$ or $\mathbf{6_F}$, is determined by the perturbative one-gluon exchange, the mass difference between members of different representations comes mainly determined by the dynamics of the light diquark, and should therefore be determined in consistency with the light baryon spectra. There is therefore a remnant ef-

fect of pseudoscalar forces in the two-light quark subsystem. Models based only on boson exchanges cannot explain the dynamics of heavy baryons, but it becomes also difficult for models based only on gluon exchanges, if consistency between light and heavy baryons is asked for. One-gluon exchange models would reduce the problem to a two-body problem controlled by the dynamics of the heaviest subsystem, and we find evidences in the spectra for contributions of both subsystems.

Our results contain the equal mass spacing rules obtained for heavy baryons by means of heavy quark symmetry and lowest order SU(3) flavor symmetry breaking to the same accuracy than experimental data. The study of the charmed sector shows a nice agreement with most of the states recently reported and it allows to predict spin and parity quantum numbers for recently measured states. The experimental confirmation of these assignments would give further support to the dynamical model used.

We are probably seeing the arrival of a possible understanding of basic features of quark dynamics in phenomenological models. The parametrization of the true degrees of freedom of any theory becomes a challenge that will allow us to advance in the understanding of low-energy realizations of QCD. Although this has been searched studying large-orbital angular momenta baryon states or subtle effects in the light baryon spectra, the combined study of light, heavy and doubly heavy baryons could be the appropriate laboratory for these achievements.

IV. ACKNOWLEDGMENTS

This work has been partially funded by Ministerio de Ciencia y Tecnología under Contract No. FPA2007-65748, by Junta de Castilla y León under Contract No. SA016A07, by the Spanish Consolider-Ingenio 2010 Program CPAN (CSD2007-00042), and by COFAA-IPN (México).

---

[1] CDF Collaboration, T. Aaltonen *et al.*, Phys. Rev. Lett. **99**, 202001 (2007).
[2] CDF Collaboration, T. Aaltonen *et al.*, Phys. Rev. Lett. **99**, 052002 (2007).
[3] D0 Collaboration, V. Abazov *et al.*, Phys. Rev. Lett. **99**, 052001 (2007).
[4] L.A. Copley, N. Isgur, and G. Karl, Phys. Rev. D **20**, 768 (1979); Erratum, Phys. Rev. D **23**, 817 (1981).
[5] K. Maltman and N. Isgur, Phys. Rev. D **22**, 1701 (1980).
[6] J.M. Richard and P. Taxil, Phys. Lett. B **128**, 453 (1983).
[7] S. Capstick and N. Isgur, Phys. Rev. D **34**, 2809 (1986).
[8] R. Roncaglia, D.B. Lichtenberg, and E. Predazzi, Phys. Rev. D **52**, 1722 (1995).
[9] B. Silvestre-Brac, Few-Body Systems **20**, 1 (1996).
[10] E. Jenkins, Phys. Rev. D **54**, 4515 (1996).
[11] K.C. Bowler *et al.*, Phys. Rev. D **54**, 3619 (1996).
[12] N. Mathur, R. Lewis, and R.M. Woloshyn, Phys. Rev. D **66**, 014502 (2002).
[13] D. Ebert, R.N. Faustov, and V.O. Galkin, Phys. Rev. D **72**, 034026 (2005).
[14] E. Bagan, M. Chabab, H.G. Dosch, and S. Narison, Phys. Lett. B **278**, 367 (1992); Phys. Lett. B **287**, 176 (1992).

[15] D.W. Wang, M.Q. Huang, and C.Z. Li, Phys. Rev. D **65**, 094036 (2002). Z.G. Wang, Eur. Phys. J. C **54**, 231 (2008).
[16] M. Karliner, B. Keren-Zura, H.J. Lipkin, and J.L. Rosner, arXiv:0706.2163 [hep-ph]; arXiv:0708.4027 [hep-ph].
[17] X. Liu, H.-X. Chen, Y.-R. Liu, A. Hosaka, and S.-L. Zhu, Phys. Rev. D **77**, 014031 (2008).
[18] W. Roberts and M. Pervin, arXiv:0711.2492 [hep-ph].
[19] D. Ebert, R.N. Faustov, and V.O. Galkin, Phys. Lett. B **659**, 612 (2008).
[20] DELPHI Collaboration, M. Feindt *et al.*, Report No. CERN-PPE/95-139, (1995).
[21] A. Valcarce, H. Garcilazo, F. Fernández, and P. González, Rep. Prog. Phys. **68**, 965 (2005).
[22] H. Garcilazo, J. Vijande, and A. Valcarce, J. Phys. G **34**, 961 (2007).
[23] J. Vijande, F. Fernández, and A. Valcarce, J. Phys. G **31**, 481 (2005).
[24] A. Valcarce, H. Garcilazo, and J. Vijande, Phys. Rev. C **72**, 025206 (2005).
[25] J. Carlson, J. Kogut, and V.R. Pandharipande, Phys. Rev. D **27**, 233 (1983); J.L. Basdevant and S. Boukraa, Z. Phys. C **30**, 103 (1986); H. Garcilazo and A. Valcarce, Phys. Rev. C **68**, 035207 (2003).
[26] G.S. Bali, Phys. Rep. **343**, 1 (2001); G.S. Bali, H. Neff, T. Düssel, T. Lippert, and K. Schilling, Phys. Rev. D **71** 114513 (2005).
[27] C. Nakamoto and H. Toki, Prog. Theor. Phys. **99**, 1001 (1998).
[28] M.B. Wise, Phys. Rev. D **45**, R2188 (1992); T.M. Yan *et al.*, Phys. Rev. D **46**, 1148 (1992).
[29] M.J. Savage, Phys. Lett. B **359**, 189 (1995).
[30] CLEO Collaboration, M. Artuso *et al.*, Phys. Rev. Lett. **86**, 4479 (2001).
[31] Belle Collaboration, K. Abe *et al.*, Phys. Rev. Lett. **98**, 262001 (2007).
[32] BaBar Collaboration, B. Aubert *et al.*, Phys. Rev. Lett. **98**, 012001 (2007).
[33] BaBar Collaboration, B. Aubert *et al.*, Phys. Rev. D **77**, 012002 (2008).
[34] Belle Collaboration, R. Mizuk *et al.*, Phys. Rev. Lett. **98**, 262001 (2007).
[35] SELEX Collaboration, A. Ocherashvili *et al.*, Phys. Lett. B **628**, 18 (2005).
[36] BaBar Collaboration, B. Aubert *et al.*, Phys. Rev. D **74**, 011103 (2006).
[37] Belle Collaboration, R. Chistov *et al.*, Phys. Rev. Lett. **97**, 162001 (2006).
[38] FOCUS Collaboration, S.P. Ratti, Nucl. Phys. Proc. Suppl. **115**, 33 (2003).

TABLE I: Quark-model parameters.

Quark masses	$m_u = m_d$ (MeV)	313
	m_s (MeV)	545
	m_c (MeV)	1659
	m_b (MeV)	5034
Boson exchanges	m_π (fm^{-1})	0.70
	m_σ (fm^{-1})	3.42
	m_η (fm^{-1})	2.77
	m_K (fm^{-1})	2.51
	$\Lambda_\pi = \Lambda_\sigma$ (fm^{-1})	4.20
	$\Lambda_\eta = \Lambda_K$ (fm^{-1})	5.20
	$g^2_{ch}/(4\pi)$	0.54
	$\theta_P(^o)$	-15
Confinement	a_c (MeV)	340
	μ_c (fm^{-1})	0.70
OGE	r_0 (fm)	see Table V

TABLE II: Masses of bottom baryons from the present work (CQC) and other approaches in the literature compared to experimental data (in MeV). In all cases we quote the central values, in Ref. [12] error bars are of the order of 100 MeV, 40 MeV in Ref. [8], 125 MeV in Ref. [17].

State	J^P	CQC	Exp.	[7]	[8]	[9]	[10]	[12]	[15]	[16]	[17]	[18]	[19]
Λ_b	$1/2^+$	5624	5624	5585	5620	5638	5623	5672			5637	5612	5622
	$1/2^+$	6106		6045		6188						6107	6086
	$1/2^-$	5947		5912		5978				5929		5939	5930
	$1/2^-$	6245		6100		6268						6180	6328
	$3/2^+$	6388		6145		6248						6181	6189
	$3/2^+$	6637		6305		6488						6401	6540
Σ_b	$1/2^+$	5807	5808	5795	5820	5845	5828	5847	5790		5809	5833	5805
	$1/2^+$	6247		6200		6370						6294	6202
	$1/2^-$	6103		6070		6155						6099	6108
	$1/2^-$	6241		6170		6245							6401
	$3/2^+$	5829	5829	5805	5850	5875	5852	5871	5820		5835	5858	5834
	$3/2^+$	6260		6250		6385						6308	6222
Ξ_b	$1/2^+$	5801	5793		5810	5806	5806	5788		5788	5780	5844	5812
	$1/2^+$	6258				6306							6264
	$1/2'^+$	5939			5950	5941	5950	5936			5903	5958	5937
	$1/2'^+$	6360				6416							6327
	$1/2^-$	6109				6116				6106		6108	6119
	$1/2^-$	6223				6236						6192	6238
	$3/2^+$	5961			5980	5971	5968	5959			5929	5982	5963
	$3/2^+$	6373				6356						6294	6341
Ω_b	$1/2^+$	6056			6060	6034	6061	6040		6052	6036	6081	6065
	$1/2^+$	6479				6504						6472	6440
	$1/2^-$	6340				6319						6301	6352
	$1/2^-$	6458				6414							6624
	$3/2^+$	6079			6090	6069	6074	6060	6060	6083	6063	6102	6088
	$3/2^+$	6493				6519						6478	6518

TABLE III: Masses, in MeV, of different bottom baryons with two-light quarks with (Full) and without ($V_\pi = 0$) the contribution of the one-pion exchange potential. The same results have been extracted from Table III of Ref. [24] for strange baryons. ΔE stands for the difference between both results.

State	Full	$V_\pi = 0$	ΔE
$\Sigma_b(1/2^+)$	5807	5822	-15
$\Sigma_b(3/2^+)$	5829	5844	-15
$\Lambda_b(1/2^+)$	5624	5819	-195
$\Lambda_b(3/2^+)$	6388	6387	$+1$
State	$V_{CON} + V_{OGE} + V_\pi$	$V_{CON} + V_{OGE}$	ΔE
$\Sigma(1/2^+)$	1408	1417	-9
$\Sigma(3/2^+)$	1454	1462	-8
$\Lambda(1/2^+)$	1225	1405	-180

TABLE IV: Mass difference (in MeV) between Σ_i and Λ_i states for different flavor sectors.

Mass difference	Exp.	CQC	[9]	[13, 19]	[17]	[18]
$\Sigma(3/2^+) - \Lambda(1/2^+)$	269	260	–	–	–	–
$\Sigma(3/2^+) - \Sigma(1/2^+)$	195	169	–	–	–	–
$\Sigma_c(3/2^+) - \Lambda_c(1/2^+)$	232	217	250	221	263	251
$\Sigma_c(3/2^+) - \Sigma_c(1/2^+)$	64	67	80	79	123	64
$\Sigma_b(3/2^+) - \Lambda_b(1/2^+)$	209	205	237	212	198	246
$\Sigma_b(3/2^+) - \Sigma_b(1/2^+)$	22	22	30	29	26	25

TABLE V: $r_0^{q_i q_j}$ in fm.

(q_i, q_j)	$r_0^{q_i q_j}$
(n, n)	0.530
(s, n)	0.269
(n, c)	0.045
(s, c)	0.029
(n, b)	0.028
(s, b)	0.017

TABLE VI: Equal spacing rules of Eqs. (5) and (6) for bottom baryon masses obtained in this work (in MeV).

	CQC
$M_{\Sigma_b} + M_{\Omega_b}$	11863
$2\,M_{\Xi_b'}$	11878
$M_{\Sigma_b^*} + M_{\Omega_b^*}$	11908
$2\,M_{\Xi_b^*}$	11922
$\delta_{\Sigma_b} + \delta_{\Omega_b}$	45
$2\delta_{\Xi_b}$	44

TABLE VII: Equal spacing rule of Eq. (7) for different models in the literature. Masses are in MeV.

Mass difference	CQC	[8]	[9]	[10]	[11]	[12]	[17]	[18]	[19]
$\Xi_b'(1/2^+) - \Sigma_b(1/2^+)$	132	130	96	122	130	89	94	125	132
$\Omega_b(1/2^+) - \Xi_b'(1/2^+)$	117	110	93	111	90	104	133	123	128
$\Xi_b(3/2^+) - \Sigma_b(3/2^+)$	132	130	96	116	120	88	94	124	129
$\Omega_b(3/2^+) - \Xi_b(3/2^+)$	118	110	93	106	100	101	134	120	125

TABLE VIII: Masses of charmed baryons from the present work (CQC) and other approaches in the literature compared to experimental data (in MeV). Those data with a question mark stand for recently measured states whose quantum numbers are not determined and they are confronted against the possible corresponding theoretical state. In all cases we quote the central values, in Ref. [12] error bars are of the order of 100 MeV, 40 MeV in Ref. [8].

State	J^P	CQC	Exp.	[7]	[8]	[9]	[10]	[12]	[15]	[17]	[18]	[19]
Λ_c	$1/2^+$	2285	2286	2265	2285	2285	2284	2290		2271	2268	2297
	$1/2^+$	2785	2765?	2775		2865					2791	2772
	$1/2^-$	2627	2595	2630		2635					2625	2598
	$1/2^-$	2880	2880?	2780		2885					2816	3017
	$3/2^+$	3061		2910		2930					2887	2874
	$3/2^+$	3308		3035		3160					3073	3262
	$5/2^+$	2888	2880?	2910		2930					2887	2883
Σ_c	$1/2^+$	2435	2454	2440	2453	2455	2452	2452	2470	2411	2455	2439
	$1/2^+$	2904		2890		3025					2958	2864
	$1/2^-$	2772	2765?	2765		2805					2748	2795
	$1/2^-$	2893		2840		2885						3176
	$3/2^+$	2502	2518	2495	2520	2535	2532	2538	2590	2534	2519	2518
	$3/2^+$	2944	2940?	2985		3065					2995	2912
	$3/2^-$	2772	2800?	2770		2805					2763	2761
Ξ_c	$1/2^+$	2471	2471		2468	2467	2468	2473		2432	2492	2481
	$1/2^+$	3137	3123?			2992						2923
	$1/2'^+$	2574	2578		2580	2567	2583	2599		2508	2592	2578
	$1/2'^+$	3212				3087						2984
	$1/2^-$	2799	2792			2792					2763	2801
	$1/2^-$	2902				2897					2859	2928
	$1/2^-$	3004	2980?			2993						3186
	$3/2^+$	2642	2646		2650	2647	2644	2680		2634	2650	2654
	$3/2^+$	3071	3076?			3057					2984	3030
	$5/2^+$	3049	3055?			3057						3042
	$5/2'^+$	3132	3123?			3167						3123
Ω_c	$1/2^+$	2699	2698		2710	2675	2704	2678		2657	2718	2698
	$1/2^+$	3159				3195					3152	3065
	$1/2^-$	3035				3005					2977	3020
	$1/2^-$	3125				3075						3371
	$3/2^+$	2767	2768		2770	2750	2747	2752	2760	2790	2776	2768
	$3/2^+$	3202				3235					3190	3119

TABLE IX: Possible model states and spin-parity assignments for recently discovered charmed baryons. The 'star' indicates radial excitations.

Experimental resonance (MeV)	Model states
Λ_c or Σ_c	
2765	$\Sigma_c(1/2^-)$ or $\Lambda_c(1/2^+)^*$
2880	$\Lambda_c(1/2^-)^*$ or $\Lambda_c(5/2^+)$
2940	$\Sigma_c(3/2^+)^*$
2800	$\Sigma_c(3/2^-)$
Ξ_c or Ξ_c'	
3055	$\Xi_c(5/2^+)$
3123	$\Xi_c(1/2^+)^*$ or $\Xi_c'(5/2^+)$
2980	$\Xi_c(1/2^-)^*$
3076	$\Xi_c(3/2^+)^*$

TABLE X: Ground state $J^P = 1/2^+$ of doubly charmed and doubly bottom baryons from the present work (CQC) and other approaches in the literature. Masses are in MeV.

	Ξ_{cc}	Ω_{cc}	Ξ_{bb}	Ω_{bb}
CQC	3579	3697	10189	10293
[8]	3660	3740	10340	10370
[9]	3607	3710	10194	10267
[12]	3588	3698	–	–
[18]	3676	3815	10340	10454

TABLE XI: Excitation spectra of doubly charmed and doubly bottom baryons ($M(J^P) - M(1/2^+)$) from the present work (CQC) and other approaches in the literature. Masses are in MeV.

State	J^P	CQC	[8]	[9]	[12]	[18]
	$3/2^+$	29	30	41	20	27
	$3/2^{+*}$	312		386		238
Ξ_{bb}	$1/2^{+*}$	293		355		236
	$1/2^-$	217		262		153
	$1/2^{-*}$	423		462		370
	$3/2^+$	28	30	38	19	32
	$3/2^{+*}$	329		383		267
Ω_{bb}	$1/2^{+*}$	311		359		239
	$1/2^-$	226		265		162
	$1/2^{-*}$	390		410		309
	$3/2^+$	77	80	93	70	77
	$3/2^{+*}$	446		486		366
Ξ_{cc}	$1/2^{+*}$	397		435		353
	$1/2^-$	301		314		234
	$1/2^{-*}$	439		472		398
	$3/2^+$	72	40	83	63	61
	$3/2^{+*}$	463		498		373
Ω_{cc}	$1/2^{+*}$	415		445		365
	$1/2^-$	312		317		231
	$1/2^{-*}$	404		410		320